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Effect of ion-parallel viscosity on the propagation of Alfvén surface waves

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The paper analyzes the damping of the Alfvén surface waves via ion parallel viscosity at a single magnetic interface. The dispersion relation is obtained and characteristics curves are drawn for the real and imaginary phase speeds. The modes thus obtained are two damped Alfvén modes propagating in a way such that when one mode dies new mode appears after a certain propagation gap. The results are applicable for the situation in solar wind at AU for values obtained from the spacecraft data.

1. Introduction

Alfvén waves have been widely discussed in space plasma and their ubiquitous presence in the solar wind was demonstrated by [1]. They lose energy as they propagate outward from the Sun. If we consider solar wind as the part of the corona we can undoubtfully say that Alfvén waves lead to coronal heating. The wave damping in solar wind is not well understood. In what follows we study the viscous damping of Alfvén surface waves propagating at the magnetic interface in the solar wind. The Braginskii viscosity ([2], [3], [4] and [5]) is a tensor with terms η_0, η_1, η_2, describing viscous dissipation and terms proportional to η_3 and η_4 as nondissipative and describe wave dispersion related to the finite ion gyroradius. Since $\omega_{ci}\tau_i$ can typically be of the order of 10^6 in the solar wind, where ω_{ci} is the ion cyclotron frequency and τ_i is the ion collision time, the term η_0 'parallel viscosity' becomes far more important than all other terms.

2. Basic equations

We consider an incompressible and viscous magnetofluid of uniform density under the assumption, when $\omega_c\tau \gg 1$. Since the viscous dissipation is dominated by the term proportional to ion-parallel viscosity, conventionally denoted by η_0^i, the viscous term gets reduced to ([6] and [7])

$$-\eta_0^i \nabla \cdot [(I - 3\hat{\mathbf{B}}\hat{\mathbf{B}})\hat{\mathbf{B}}\hat{\mathbf{B}} : \nabla \mathbf{v}], \tag{1}$$

where $\hat{\mathbf{B}}$ is a unit vector in the direction of magnetic field. In terms of cartesian coordinates equation (1) simplifies to

$$+\eta_0^i \left(-\frac{\partial^2}{\partial x \partial z}, -\frac{\partial^2}{\partial y \partial z}, 2\frac{\partial^2}{\partial z^2}\right) v_z = \eta_0^i \mathbf{D} v_z. \tag{2}$$

Taking the mass density to be uniform and constant, the associated kinematic viscosity coefficient is $\nu_{ion} = \eta_0^i/\rho$.
The relevant linearized incompressible MHD set of equations when the viscous dissipation is dominative by the term proportional to ion parallel viscosity, are

$$\frac{\partial \mathbf{v}}{\partial t} = -\nabla p^T + \frac{1}{4\pi\rho}(\mathbf{B_0} \cdot \nabla)\mathbf{b} + \nu_{ion}\mathbf{D}v_z, \tag{3}$$

$$\frac{\partial \mathbf{b}}{\partial t} = \mathbf{B_0} \cdot \nabla \mathbf{v}, \tag{4}$$

$$\nabla \cdot \mathbf{v} = 0, \nabla \cdot \mathbf{b} = 0, \tag{5}$$

where $\mathbf{B_0} = B_0\hat{\mathbf{z}}$; $\mathbf{v}$ and $\mathbf{b}$ are the perturbed velocity and magnetic field, and p^T is the total pressure (plasma and magnetic).
Equations (3)-(5) can be Fourier-analysed, assuming all perturbed quantities $\alpha\, g(x) \exp(-i\omega t + ik_z)$ i.e. $\partial/\partial t = -i\omega, \partial/\partial x \neq 0, \partial/\partial y = 0$, and $\partial/\partial z = ik_z$, to obtain the second order differential equation for the $x-$ component of velocity, v_x,

$$\frac{d^2}{dx^2}v_x - m^2 v_x = 0, \tag{6}$$

where

$$m^2 = \frac{\omega^2 - k_z^2 v_A^2}{\omega^2 - k_z^2 v_A^2 + 3i\omega\nu_{ion}k_z^2}.$$

We consider plasma media occupying half spaces $x < 0$ and $x > 0$. The solution to equation (6) in the respective regions $x < 0$ and $x > 0$ is given by

$$v_{xo} = A_o e^{m_o x}, \quad x < 0, \tag{7}$$

$$v_{xe} = A_e e^{-m_e x}, \quad x > 0, \tag{8}$$

where A_o and A_e are arbitrary constants and subscripts 'o' and 'e' stand for the regions $x < 0$ and $x > 0$ respectively. We have imposed the conditions $m_o > 0$ and $m_e > 0$, and $v_x \to 0$ as $x \to \pm\infty$ to represent surface waves. Across the interface $x = 0$, we impose the boundary conditions that the normal component of velocity v_x and total pressure p^T (gas plus magnetic) must be continuous.

3. Dispersion relation and Discussion

Using the boundary conditions, we derive the dispersion relation in normalized form for the surface waves

$$(x^2 - 1 + 2ixV_0)^2 r^2 m_0^2 = m_e^2 (x^2 - a_{Ae}^2 + 2ixV_e)^2, \tag{9}$$

where

$$x = \frac{\omega}{k_z v_{Ao}}, \; V_0 = \frac{\nu_{ion,o}k_z}{v_{Ao}}, \; V_e = \frac{\nu_{ion,e}k_z}{v_{Ae}},$$

$$a_{Ae} = v_{Ae}/v_{Ao}, \quad r = \frac{\rho_o^2}{\rho_e^2},$$

$$m_o^2 = k_z^2 \frac{(x^2 - 1)}{x^2 - 1 + 3ixV_o},$$

and

$$m_e^2 = k_z^2 \frac{(x^2 - a_{Ae}^2)}{x^2 - a_{Ae}^2 + 3ixV_e}.$$

Here $\nu_{ion,o}$ and $\nu_{ion,e}$ are the kinematic viscosity coefficients, and v_{Ae} and v_{Ao} are the Alfvén velocities on either side of the interface. In the absence of ion-parallel viscosity, the dispersion relation reduces to

$$\frac{\omega^2}{k^2} = \frac{\rho_o v_{Ao}^2 + \rho_e v_{Ae}^2}{\rho_o + \rho_e} \tag{10}$$

which is the well known dispersion relation for Alfvén surface waves in an incompressible fluid. In order to know the nature of waves in our case we need to study the equation (9). On setting $V_e = \alpha V_o$,, where $\alpha = \frac{\nu_{ion,e}}{\nu_{ion,o}}$, we solve numerically the dispersion relation (9) for phase speeds as a function of V_0 in the context of a situation in solar wind at 1 AU. The ratio of current plasma densities on either side of the interface, ρ_0/ρ_e is taken 0.2. The values of real and imaginary phase speeds are obtained from the values of x in units of v_{A0}. Figs. 1 and 2 show the variations of real and imaginary phase speeds with the parameter V_0 for $r = 0.04$, $a_{Ae} = 0.44$ and $\alpha = 0.5$. It is evident from the figures that the Alfvén surface waves propagating along the interface are damped waves. It is also found that there are only two damped modes of Alfvén surface waves which do not propagate simultaneously; the later mode propagates with slower speed than previous one. It is seen from figure 1 that the speed of Alfvén surface wave decreases as ion-parallel viscosity increases. This wave becomes evanescent at a critical value of V_0=0.55. After the disappearence of this mode a new second mode arises from 0.6 whose phase speed decreases with the increase in the value of the parameter V_0. It is also notable that there is a small region from $V_0 = 0.55$ to 0.6 where there is no propagation of either of the wave. This region is called a non propagation region. Figure 2 depicts the damping rate of the wave with the parameter V_0. Damping of the mode increases as V_0 increases but decreases after the value of 0.9. Thus the modes of surface waves become damped owing to ion-parallel viscosity in an incompressible fluid.

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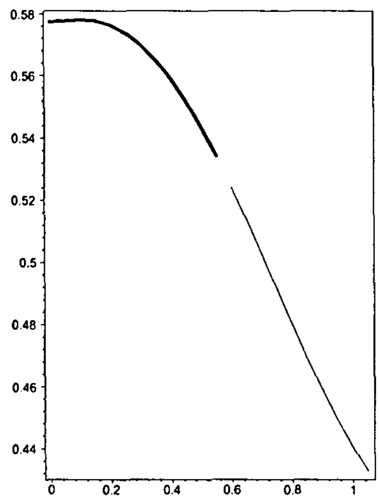

Figure 1: Variation of real phase speeds ω_R/k with parameter V_0. Dark line represents first mode while light line represents second mode of Alfvén surface waves.

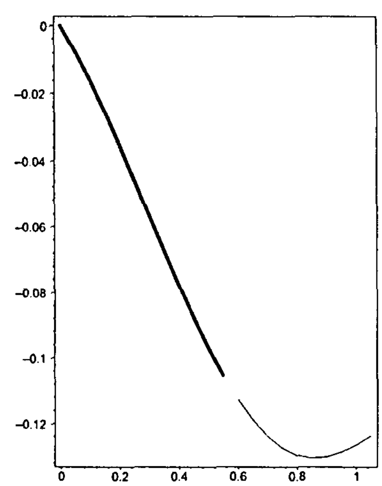

Figure 2: Variation of imaginary phase speeds ω_I/k with parameter V_0. Dark line represents first mode while light line represents second mode of Alfvén surface waves.

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